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RESEARCH MEMORANDUM

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CHARACTERISTICS OF CONVERGENT-PLUG

EXHAUST NOZZLES
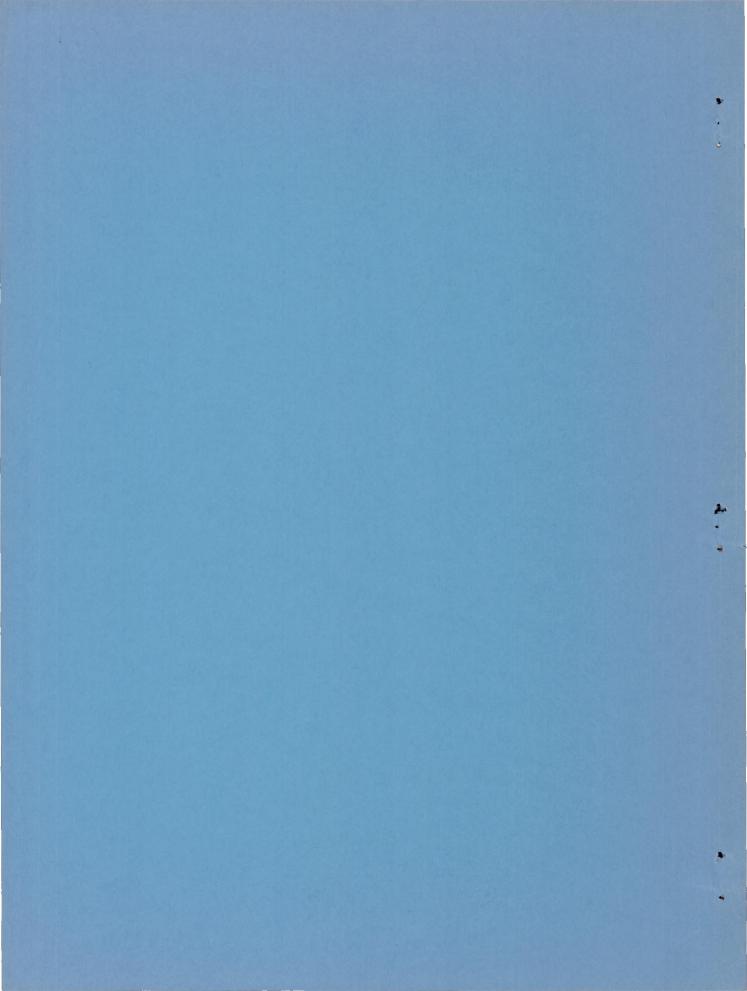
By H. George Krull and William T. Beale

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS
WASHINGTON

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EFFECT OF OUTER-SHELL DESIGN ON PERFORMANCE CHARACTERISTICS

OF CONVERGENT-PLUG EXHAUST NOZZLES

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SUMMARY

An investigation was conducted to determine the effect of outer-shell design variables on the internal performance characteristics of several plug-type nozzles designed for a pressure ratio between 6 and 12. The data were obtained over a range of nozzle pressure ratios from about 1.5 to 30.

Inlet Mach number and outer-shell angle had no effect on nozzle thrust coefficient. Outer-shell exit position, however, had a marked effect on nozzle thrust coefficient. A thrust coefficient of 0.975 was obtained when the outer-shell exit was located downstream of the point where the curved portion of the plug became tangent to the conical expansion section. The thrust coefficient decreased to 0.90 with the exit of the outer shell located at the maximum diameter of the plug.

For choked flow, the effective throat area decreased when either the inlet Mach number or the outer-shell angle was increased.

INTRODUCTION

The extended plug-type nozzle has been shown to possess good thrust characteristics over a wide range of pressure ratios (ref. 1). The peak thrust coefficients were about as high as those of a convergent-divergent nozzle, and were relatively insensitive to pressure ratio below the design point. These data did not necessarily represent the optimum performance of a plug nozzle, however, because no attempt was made to refine the design.

The effect of refinements in plug design on nozzle performance is reported in reference 2. The plug variables that were investigated included plug expansion-section contour (isentropic and conical), conical plug angle, and throat approach section. Peak thrust coefficients from 1 to 2 percent higher were obtained with the nozzles of reference 2 than with those of reference 1.

The configurations of references 1 and 2 had low inlet Mach numbers and arbitrary outer-shell angles. Actual nozzle-inlet Mach numbers for realistic engine designs are much higher than those of references 1 and 2. Also, in the nozzle design there is a wide choice of outer-shell exit angle and the relation of outer-shell exit position to parts of the plug contour.

An investigation was therefore conducted to determine the effects of outer-shell design variables on nozzle performance. The design variables that were investigated included nozzle-inlet Mach number, outer-shell angle, and longitudinal position of the outer-shell exit relative to the plug.
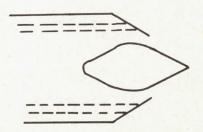
The plug nozzles were investigated over a range of nozzle pressure ratios from 1.5 to 30. A 30° conical plug was used for the entire investigation. The inlet Mach number was varied from 0.16 to 0.32 and the outer-shell angle ranged from 23° to 90°.

APPARATUS AND INSTRUMENTATION

Nozzle Configurations

The 12 conical-plug-nozzle configurations investigated are listed in table I along with the dimensions of the various parts. An exploded view of a typical configuration is shown in figure 1. All configurations had a 30° conical plug.
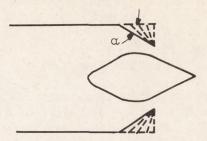
Configurations for varying inlet Mach number. - Configurations 1, 2, and 3 were used to study the effect of nozzle-inlet Mach number. The inlet Mach number was varied from 0.18 to 0.32 by changing the outer shell diameter as shown by the dashed lines in the following sketch:

The outer-shell exit was located just downstream of the point where the curved portion of the plug became tangent to the conical expansion section. The design pressure ratio of these configurations was approximately 6.8 (isentropic pressure ratio corresponding to the ratio of outer-shell exit area to throat area). The throat area was defined as the annulus area between the outer-shell exit and the plug in a plane perpendicular to the nozzle axis.
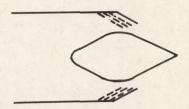
Configurations for varying outer-shell angle. - The effect of outer-shell angle was determined with configuration 1 and configurations 4 to 7. The outer-shell angle α was varied from 23° to 90° (see sketch).

The outer-shell exit position was the same as for configurations 1 to 3. The design pressure ratio of these configurations was approximately 6.2.

Configurations for varying outer-shell exit position. - The effect of outer-shell exit position was determined with configuration 2 and configurations 8 to 12. The outer-shell exit position was varied from the point of tangency of the curved portion of the plug and the conical expansion section to the hump of the plug as indicated schematically in the following sketch:

The design pressure ratios varied from 6.9 to 12.6 for these configurations. The outer-shell angle varied from 23° to 90° for these configurations except the one with the exit at the maximum diameter of the plug, where the shell angle was zero.

Installation

The nozzles were installed in a test chamber, which was connected to the laboratory combustion air and altitude exhaust facilities as shown in figures 2 and 3. The nozzles were bolted to a mounting pipe, which was freely suspended by four flexure rods that were connected to the bed plate. Pressure forces acting on the nozzle and mounting pipe, both external and internal, were transmitted from the bed plate through a flexure-plate-supported bell crank and linkage to a balanced-air-pressure diaphragm force-measuring cell. Pressure differences across the nozzle

and mounting pipe were maintained by labyrinth seals around the mounting pipe, which separated the nozzle inlet air from the exhaust. The space between the two labyrinth seals was vented to the test chamber. This decreased the pressure differential across the second labyrinth and prevented a pressure gradient on the outside of the diffuser section due to an air blast from the labyrinth seal.

Instrumentation

Pressures and temperatures were measured at various stations, which are indicated in figure 2. Total- and wall static-pressure measurements at station 1 were used to compute inlet momentum, and total- and static-pressure measurements (stream and wall static) at station 2 were used to compute air flow. Total pressure and temperature were measured at the nozzle inlet (station 3). Ambient-exhaust pressure was provided at station O, and a static-pressure survey was made on the outside walls of the bellmouth inlet. Wall static pressures were measured along the surfaces of each of the plugs (from maximum diameter to downstream tip).

PROCEDURE

Performance data for each configuration were obtained over a range of nozzle pressure ratios at a constant air flow. The nozzle pressure ratio was varied from about 1.5 to the maximum obtainable. Maximum pressure ratio varied from configuration to configuration because of the varying throat areas and the limiting air-handling capacity of the air supply and exhauster equipment.

The thrust coefficient was calculated by dividing the actual jet thrust by the ideal thrust. The actual jet thrust was computed from the force measured by the balanced-air-pressure diaphragm and from pressure and temperature measurements made throughout the setup. The ideal jet thrust was calculated as the product of the measured mass flow and the isentropic jet velocity based on the nozzle pressure ratio and the inlet temperature. The methods of calculation used in this report and the symbols are shown in appendixes A and B, respectively.

RESULTS AND DISCUSSION

The effects of varying the outer-shell geometry on the performance of a convergent plug nozzle were determined with nozzles designed for pressure ratios (isentropic pressure ratio corresponding to the ratio of the outer-shell exit area to the throat area) between 6 and 13. As shown in reference 2, a 30° plug gives the highest performance (for a conical plug) for these design pressure ratios and was therefore used for all configurations reported herein.

Effect of Inlet Mach Number on Performance

The thrust coefficients of the plug nozzles investigated were not affected by variations in inlet Mach number. The thrust coefficients were also relatively insensitive to nozzle pressure ratio with a peak of about 0.975 (same results as reported in ref. 2). This is shown in figure 4, which is a plot of thrust coefficient and air-flow parameter against nozzle pressure ratio. The nozzle-inlet Mach number was varied from 0.18 to 0.32 by holding the plug diameter constant and decreasing the diameter of the outer shell. For this particular plug design, the upper limit of the inlet Mach number was 0.32 because the Mach number at the plug hump had reached unity (flow area at hump equal to throat area). The nozzle would then operate somewhat underexpanded at the original design pressure ratio.

The air-flow parameter showed a decrease at the high inlet Mach number. The theoretical value of the air-flow parameter for choked flow is shown by a dashed line on figure 4.

Effect of Outer-Shell Angle on Performance

The thrust coefficient was not affected by variations in outer-shell angle. The thrust coefficients for nozzles having outer-shell angles from 23° to 90° are shown in figure 5 plotted against nozzle pressure ratio. The thrust characteristics were the same as those of figure 4. For this particular plug design, the lower limit of the outer-shell angle was 23°. Any further decrease in angle would have resulted in the formation of a convergent-divergent flow passage by shifting the throat upstream of the outer-shell exit.

The air-flow parameter, which is also shown in figure 5, decreased as the outer-shell angle was increased. This decrease in air-flow parameter with decreasing angle is presumably due to changes in the vena contracta downstream of the exit.

Effect of Outer-Shell Exit Position on Performance

The use of a translatable-type variable-area nozzle would require variation in outer-shell exit position. The effect of outer-shell exit position on nozzle performance is shown in figure 6. Thrust coefficient and air-flow parameter are plotted against nozzle pressure ratio for a range of length ratios L_s/L_p from zero to 0.34. These nozzles had various outer-shell angles and inlet Mach numbers but these variables have been shown to have no effect on nozzle thrust coefficient. Moving the outer-shell exit upstream onto the curved portion of the plug lowered the entire thrust coefficient curve for length ratios below 0.25, but the general insensitivity of thrust coefficient to pressure ratio

was unchanged. The peak thrust coefficients from figure 6 are plotted against outer-shell exit position in figure 7. The peak thrust coefficient was decreased from 0.975 to 0.90 by translating the outer-shell exit position from a point just downstream of the tangency of the curved portion of the plug and the conical expansion section to the maximum diameter of the plug. This reduction in thrust coefficient is due to a decrease in the pressure on the plug caused by a Prandtl-Meyer expansion on the plug (see ref. 2). This decrease in pressure is shown by plots of the pressure distribution along the plug in figure 8 for nozzles with length ratios of 0.26, 0.128, and zero. As the outer-shell exit was moved upstream on the curved portion of the plug, the pressure force on the plug decreased.

In general, the air-flow parameters (fig. 6) increased as the exit approached the plug hump because the actual throat area approached the same plane as the arbitrarily defined throat area.

SUMMARY OF RESULTS

The effects of outer-shell design variables on the internal performance characteristics of several plug-type nozzles were obtained over a range of nozzle pressure ratios from 1.5 to 30. These nozzles had design pressure ratios between 6 and 12. Inlet Mach number and outer-shell angle had no effect on nozzle thrust coefficient. Outer-shell exit position, however, had a marked effect on nozzle thrust coefficient. A thrust coefficient of 0.975 was obtained when the outer-shell exit was located downstream of the point where the curved portion of the plug became tangent to the conical expansion section. The thrust coefficient decreased to 0.90 with the outer-shell exit located at the maximum diameter of the plug. This decrease in thrust coefficient was due to a reduction in pressure on the plug surface caused by a Prandtl-Meyer expansion on the plug.

For choked flow, the effective throat area decreased when either the inlet Mach number or the outer-shell angle was increased.

Lewis Flight Propulsion Laboratory
    National Advisory Committee for Aeronautics
        Cleveland, Ohio, November 30, 1954

APPENDIX A

METHODS OF CALCULATION

Air flow. - The nozzle air flow was calculated as

$$W_{a,2} = \frac{p_2 A'_2}{\sqrt{RT_3}} \sqrt{\frac{2g\gamma}{\gamma - 1}\left[\left(\frac{P_2}{p_2}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]\left(\frac{P_2}{p_2}\right)^{\frac{\gamma-1}{\gamma}}}$$

where γ was assumed to be 1.4.

Thrust. - The jet thrust was defined as

$$F_j = \frac{W_{a,2}}{g} V_e + A_{f,t}(p_t - p_0) + \int_0^{A_{p,t}} p \, dA_p - p_t A_{p,t}$$

or as defined in the conventional manner

$$F_j = \frac{W_{a,2}}{g} \overline{V}_e + A_s(\overline{p}_e - p_0)$$

where $\overline{V}_e$ and $\overline{p}_e$ are effective values. The actual jet thrust was calculated by the equation

$$F_j = \frac{W_{a,2}}{g} V_1 + p_1 A'_1 - p_{bm} A'_1 + A_L(p_{bm} - p_0) - F_d$$

where F_d was obtained from balanced-air-pressure measurements.

The ideally available jet thrust, which was based on measured mass flow, was calculated as

$$F_i = W_{a,2} \sqrt{\frac{2R}{g} \frac{\gamma}{\gamma-1} T_3 \left[1 - \left(\frac{p_0}{P_3}\right)^{\frac{\gamma-1}{\gamma}}\right]}$$

Thrust coefficient. - The thrust coefficient is defined as the ratio of the actual to ideal jet thrust:

$$C_T = \frac{F_j}{F_i}$$

APPENDIX B

SYMBOLS

The following symbols are used in this report:

A outside area, sq ft

A' inside area, sq ft

A_f flow area (annulus between outer-shell exit area and plug in plane perpendicular to plug axis), sq ft

A_L pipe area under labyrinth seal, sq ft

A_p plug projected area, sq ft

A_s exit area of outer shell, sq ft

C_T thrust coefficient

F thrust, lb

F_d balanced-air-pressure-diaphragm reading, lb

g acceleration due to gravity, 32.174 ft/sec^2

L_p distance from maximum diameter of plug to downstream tip of plug

L_s distance from maximum diameter of plug to outer-shell exit

P total pressure, lb/sq ft

p static pressure, lb/sq ft

p_{bm} integrated static pressure acting on outside of bellmouth inlet to station 2, lb/sq ft

R gas constant, 53.3 ft-lb/(lb)($^\circ$R) for air

T total temperature

V velocity, ft/sec

W_a measured air flow, lb/sec

α outer-shell angle, deg

δ   ratio of total pressure at nozzle inlet to absolute pressure at NACA standard sea-level conditions

γ   ratio of specific heats

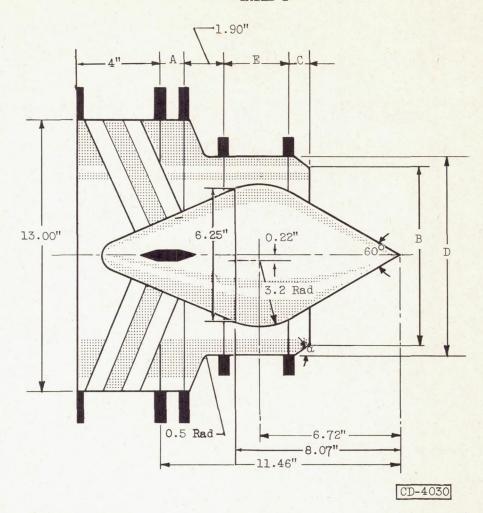θ   ratio of total temperature at nozzle inlet to absolute temperature at NACA standard sea-level conditions

Subscripts:

e   nozzle exit

i   ideal

j   jet

p   plug

t   throat

w   plug surface or wall

0   exhaust or ambient

1   inlet

2   diffuser inlet

3   nozzle inlet

REFERENCES

1. Ciepluch, Carl C., Krull, H. George, and Steffen, Fred W.: Preliminary Investigation of Performance of Variable-Throat Extended-Plug-Type Nozzles over Wide Range of Nozzle Pressure Ratios. NACA RM E53J28, 1954.

2. Krull, H. George, and Beale, William T.: Effect of Plug Design on Performance Characteristics of Convergent-Plug Exhaust Nozzles. NACA RM E54H05, 1954.

TABLE I

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Configuration	A, in.	B, in.	C, in.	D, in.	E, in.	α, deg	$\dfrac{\text{Shell exit area}}{\text{Throat area}}$, $A_s/A_{f,t}$	Design pressure ratio	Throat area, $A_{f,t}$, sq in.
1	0	8.86	4.13	13.00	0.91	27	1.53	6.5	40.41
2	1.03	8.58	1.00	9.72	3.15	36	1.58	6.9	36.58
3	1.03	8.58	1.00	9.43	3.15	36	1.59	7.0	36.40
4	0	8.86	4.84	13.00	0.18	23	1.51	6.3	40.74
5	0	8.86	2.12	13.00	2.92	44	1.50	6.2	41.22
6	0	8.87	1.03	13.00	4.00	63	1.49	6.1	41.38
7	0	8.86	0	13.00	5.08	90	1.46	5.9	42.33
8	2.04	9.72	0	9.72	3.15	90	1.98	10.4	37.55
9	.52	8.58	1.00	9.72	3.15	36	1.82	9.0	31.84
10	.03	9.24	.57	9.72	3.15	23	2.05	11.1	32.64
11	.03	9.24	0	9.72	3.15	90	2.20	12.6	30.54
12	.06	9.73	2.80	9.73	0	0	1.96	10.2	37.83
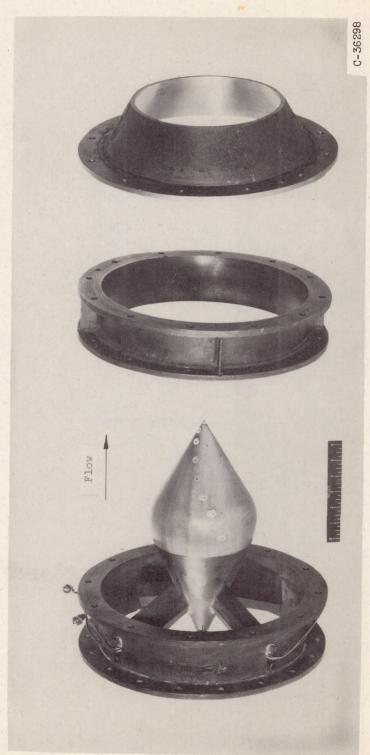
Figure 1. - Exploded view of conical plug nozzle.

Station   1   2   3   0
        (Inlet)   (Air-flow   (Nozzle inlet) (Ambient-exhaust
                   measurement)   nozzle exit)

Vent line   Test chamber

Flexure rod

Inlet-air
line

Mounting   Test
pipe   nozzle

Flow

Bellmouth inlet

Labyrinth seals

Diffuser

Exhaust line

Bed plate   Bell crank

Thrust-measuring
cell

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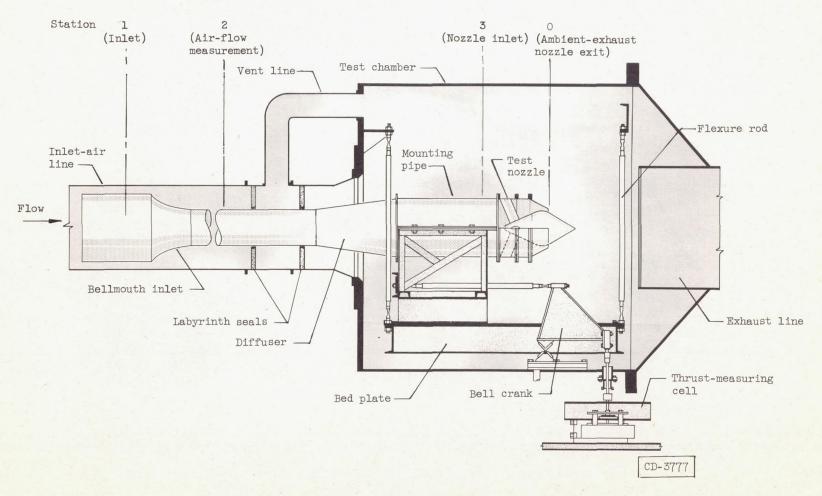
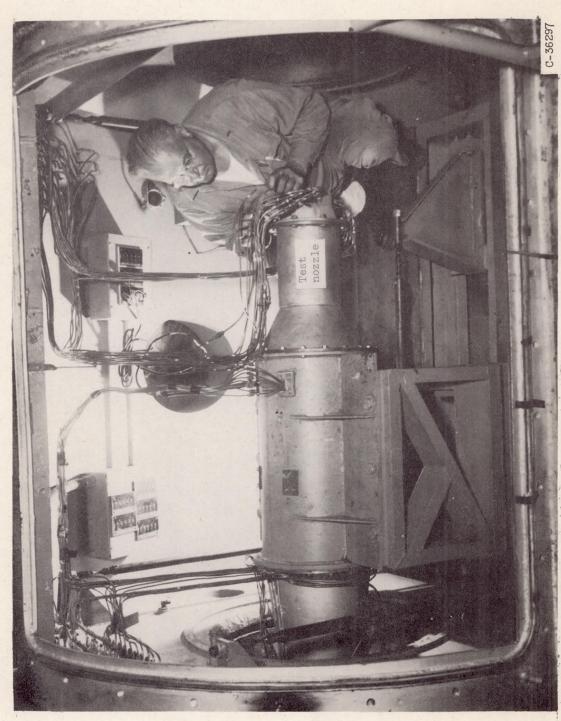Figure 2. - Schematic drawing of nozzle in test chamber.
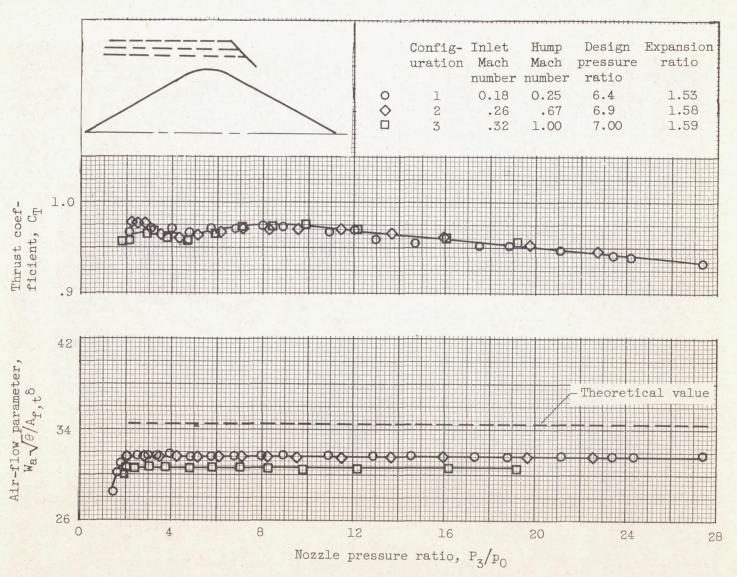
Figure 3. – Installation of nozzle in test chamber.

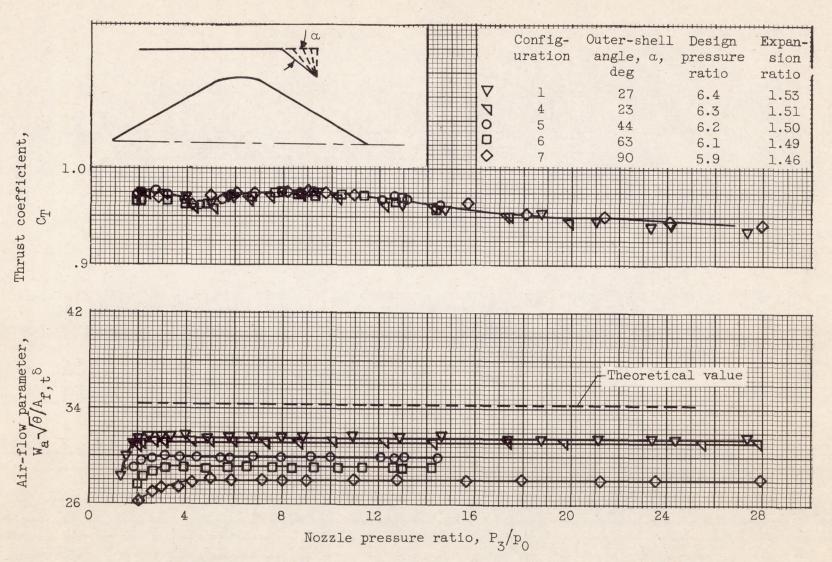Figure 4. - Effect of inlet Mach number on nozzle performance.

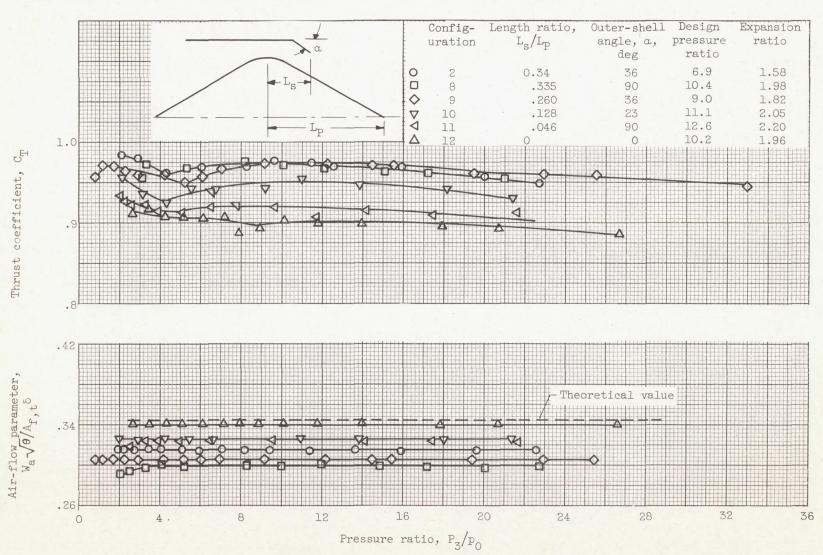Figure 5. - Effect of outer-shell angle on nozzle performance.

Config- uration	Outer-shell angle, α, deg	Design pressure ratio	Expan- sion ratio
1	27	6.4	1.53
4	23	6.3	1.51
5	44	6.2	1.50
6	63	6.1	1.49
7	90	5.9	1.46

Figure 6. - Effect of outer-shell exit position on nozzle performance.

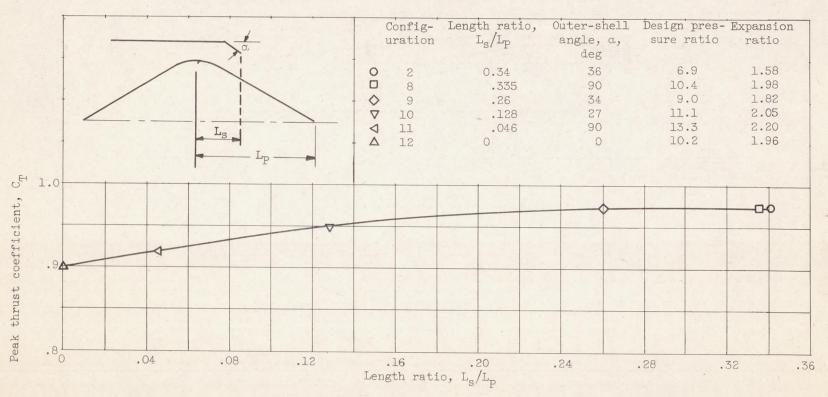| Config-uration	Length ratio, L_S/L_P	Outer-shell angle, α, deg	Design pressure ratio	Expansion ratio
○ 2	0.34	36	6.9	1.58
□ 8	.335	90	10.4	1.98
◇ 9	.26	34	9.0	1.82
▽ 10	.128	27	11.1	2.05
◁ 11	.046	90	13.3	2.20
△ 12	0	0	10.2	1.96

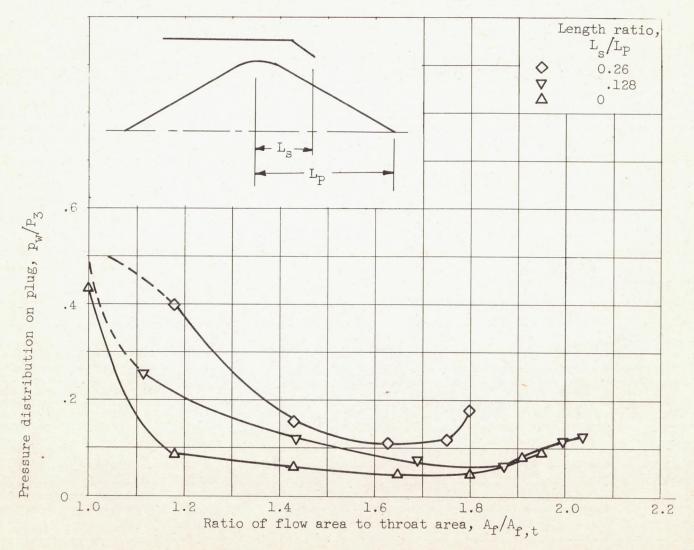Figure 7. - Effect of outer-shell exit position on peak thrust coefficient.

Figure 8. - Comparison of plug pressure distributions at nozzle pressure ratio of 20 for three outer-shell exit positions.

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